# THE LOMBARD EFFECT IN OPEN PLAN OFFICES

P Leonard Max Fordham LLP
A Chilton Max Fordham LLP

## 1 INTRODUCTION

The methods described in BS 3382-3:2012[1] for measuring the room acoustic parameters of open plan offices assume the sound power spectrum for normal speech. This is equivalent to an A-weighted sound pressure level of 57.4dB at a distance of 1m, for an omni-directional source or 59.5dB for a directional source.

However, there may be situations in which occupant speech level will be higher than this because of the Lombard effect i.e. occupants raise their voice in response to the background level in order to enhance its audibility. This situation is most likely to arise in open plan offices where there is a relatively high density of people talking as this will result in a higher background noise level.

This paper presents the results of measurements made at an open plan contact centre which indicate that there is evidence of occupants speaking at raised levels due to the Lombard effect. The significance of the results is discussed in terms of the potential effect on activity noise levels and on parameters such as distraction and privacy distances.

Large open plan offices are not typically well represented by a fully diffuse, i.e. Sabine, room response. In such cases, analysis of the room acoustics requires the use of a geometrical acoustic computer model. Consideration is given to how the Lombard effect might be implemented in the design of these types of spaces.

## 2 VOICE LEVELS IN OPEN PLAN OFFICES

### 2.1 The Lombard Effect

It is a well-known phenomenon that people speaking in a room will change the level of their voice in response to a change in background noise, in order to compensate for the masking effect of the background noise.

This is called the Lombard effect, named after Etienne Lombard who discovered the effect in 1909. A relation between vocal effort and the ambient noise level is given in ISO 9921:2003[2] and shown here in Figure 1. The Lombard effect can be characterized by the gradient of the slope, which is indicated in ISO 9921 to be approximately between 0.55 and 0.65.

Therefore, for every 1dB increase in background noise level, one can expect a 0.55-0.65dB increase in speech level. This slope is valid for ambient noise levels above 45dBA. Below this level the Lombard effect is still present but to a lesser degree.

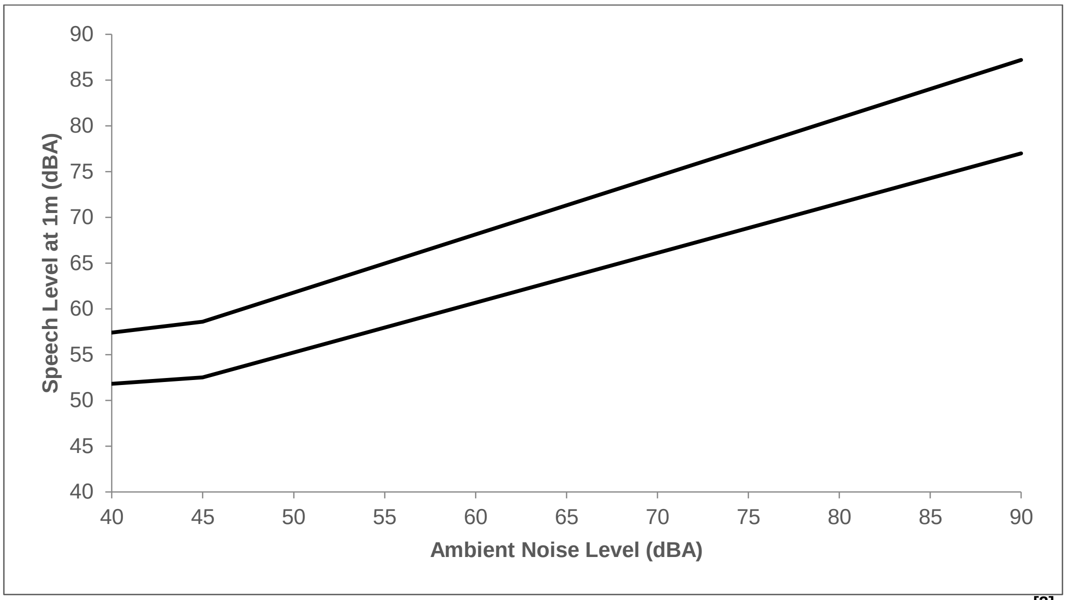


**Figure 1 - Relation between the range of vocal effort and the ambient-noise level[2]**

A study by Lazarus[3] found that the average speech level rise is about 0.5-0.6dB/dB and that the average speech and noise levels at which this rise begins are 55dBA and 45dBA respectively. Therefore, for ambient noise levels above 45dBA, the estimated speech level, taking into account the Lombard effect, can be described approximately by:

$$L_{S,A,1m} = 55 + c\left(L_{N,A} - 45\right) \quad (1)$$

Where $L_{S,A,1m}$ is the speech level at 1m, $L_{N,A}$ is the ambient noise level and $c$ is the Lombard coefficient. Consequently, a speech level at 1m of 59.5dBA, as used in BS 3382-3:2012, is predicted by equation 1 when the ambient noise level is equal to 54dBA (presuming a Lombard coefficient of 0.5).

### 2.2 Ambient Noise Levels in Typical Open Plan Offices

Most research to date on open plan offices assumes that speech levels are, on average, constant in level and approximately equal to 'normal speech' as defined in ANSI S 3.5-1997[4] and adopted in BS 3382-3:2012.

As discussed in the previous section, the Lombard effect would only cause speech levels to rise above this level in ambient noise level environments of approximately 54dBA or above.

A study of 9 open plan offices by Warnock & Chu[5] found ambient noise levels to range from 41dBA to 52dBA with an average level for the nine offices of 47dBA. A survey of 7 open plan offices by Moreland[6] found ambient noise levels to range from 43dBA to 48dBA with an average for the seven offices of 45dBA. Nilsson & Hallström[7] measured ambient noise levels in 4 open plan offices ranging from 46dBA to 53dBA with an average for the 5 offices of 50dBA.

These studies, summarised in Table 1, suggest that for the majority of typical open plan offices, the ambient noise levels are unlikely to be high enough to result in speech levels rising above the 'normal speech' level due to the Lombard effect.

| Study | No. Offices | Measured Ambient Noise Level (dBA) Min | Max | Average |
|---|---|---|---|---|
| Warnock & Chu | 9 | 41 | 52 | 47 |
| Moreland | 7 | 43 | 48 | 45 |
| Nilsson & Hallström | 4 | 46 | 53 | 50 |
| Summary | 20 | 41 | 53 | 47 |

**Table 1 - Summary of open plan office ambient noise level studies**

### 2.3 Ambient Noise Levels in Contact Centres

Contact centres are more densely occupied than typical open plan offices and those occupants are also likely to spend a greater percentage of time speaking, resulting in higher ambient noise levels.

Trompette & Chatillon[8] conducted a survey of ambient noise levels at 21 call centers with measurements ranging from 50dBA to 62dBA and an average level for the 21 call centers of 58dBA. These results are shown in Figure 2.

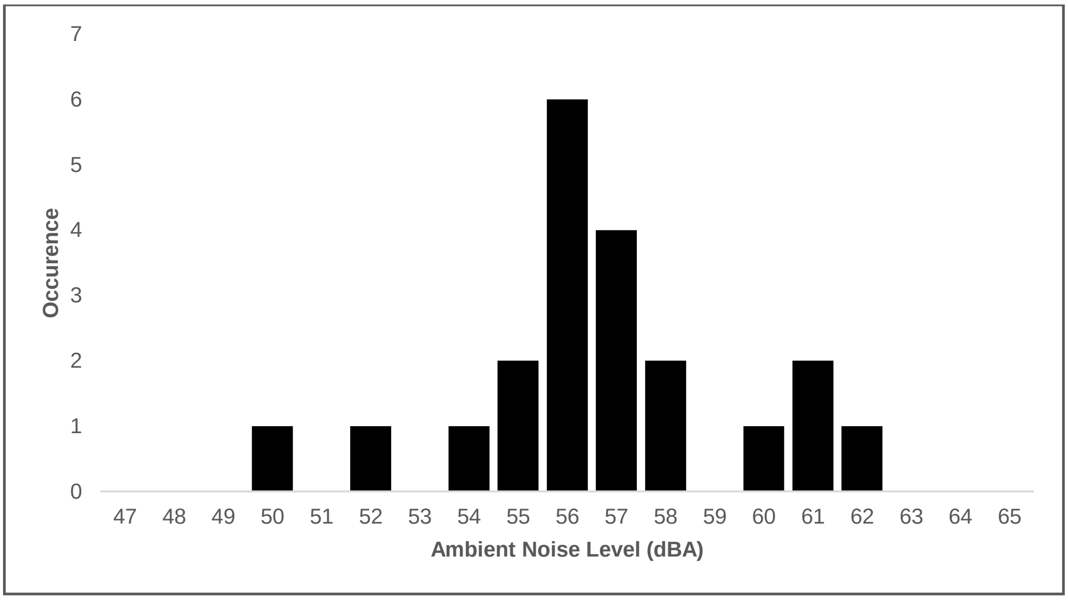


**Figure 2 - Ambient noise levels in contact centers (Ref: Trompette & Chatillon)**

The minimum, maximum and average levels as measured for contact centers are all 9-10dBA higher than as measured for typical open plan offices. It is, therefore, more likely that the average speech level of occupants will be raised above the “normal speech” level due to the Lombard effect.

Consequently, if predictions of activity noise levels are to be made for contact centers, or other high occupational density open plan offices, then the Lombard effect should be taken into account in order to avoid underestimating noise levels.

# 3 NOISE LEVEL MEASUREMENTS IN A CONTACT CENTER

Ambient noise level measurements were made at a large contact centre in the UK. The office space has a floor area of approximately 1000m² with 256 formal desk spaces.

## 3.1 Reverberation Time

Reverberation time measurements were made within the office in order to estimate the extent of acoustic absorption in the space. 3 source positions were used along with 6 receiver positions for each source, giving a total of 18 measurements.

The mid-frequency (400Hz – 2500Hz) third-octave band average reverberation time was found to be 0.60 seconds with a standard deviation of 0.05 seconds.

## 3.2 Ambient Noise Levels

In order to assess the noise levels experienced within the contact centre, noise monitoring equipment was set up at a representative desk seating location for a period of 34 hours. A summary of the variation in noise levels can be seen in Figure 3.

The average noise level measured within the office during operational hours (8am – 8pm) was 62.2dB $L_{Aeq}$ with a slightly higher level during the core offices hours (9am – 5pm) of 63.4dB $L_{Aeq}$.

There is a masking noise system operating at the contact centre and during the night-time period, the baseline level produced by the masking noise system can be seen to be approximately 47.4dBA.

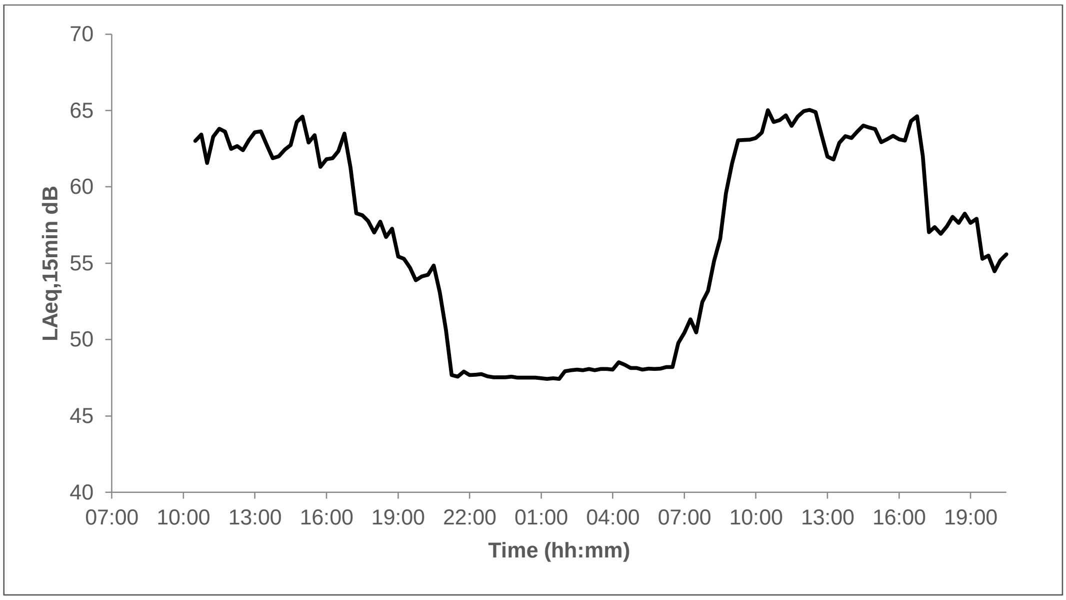


**Figure 3 - Ambient noise levels measured in the contact center**

## 3.3 Occupancy Levels

The contact centre operator was able to provide expected occupancy levels for the office during the survey period at a resolution of 15-minute intervals based upon employee rota data for the contact centre.

The occupancy data during the survey period is shown in Figure 4.

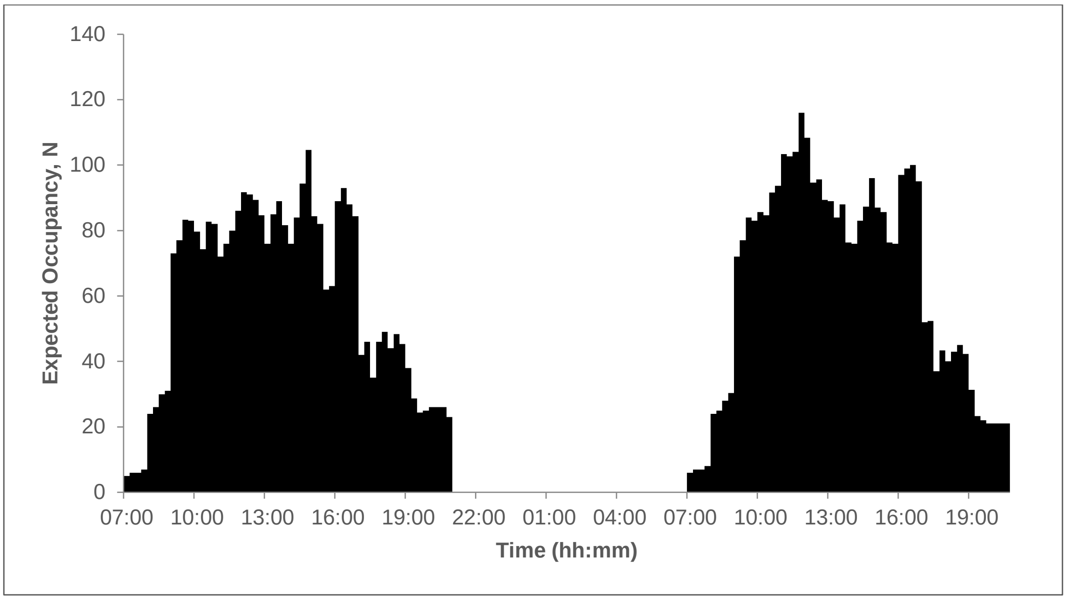


**Figure 4 - Expected contact centre occupancy during noise survey**

# 4 OBSERVED LOMBARD EFFECT

By making the assumption that:

- on average, speech from each occupant is contributing equally towards the overall ambient noise level,
- the measured noise level is predominantly a reverberant noise level,
- the number of occupants, N, is large enough such that the percentage of time an occupant is speaking can, on average, be assumed constant,

then the relationship between ambient noise level and speech level can be described by:

$$L_{NA} = L_w + 10\log_{10}(N) + 10\log_{10}\left(\frac{4}{Rc}\right) \quad (2)$$

Where $L_w$ is the average speech sound power level per occupant, $N$ is the number of occupants and $Rc$ is the room constant. The last term in equation 2 describes the reverberant effect of the room and is a constant value. For simplicity, this term will be set to equal $R$ to represent the “room effect” and the formula rearranged to:

$$L_{NA} - 10\log_{10}(N) = L_w + R \quad (3)$$

$L_w + R$ is a term representing the speech level and is equal to the reverberant noise level of one voice. This can be calculated for each 15-minute period during the noise survey and plotted against the corresponding ambient noise level, $L_{NA}$. This can be seen in Figure 5.

There are four outlying values which are considered to be erroneous. These values all occur between 7am and 8am, where it is hypothesised that there may be additional noise associated with arrival of the first occupants on site.

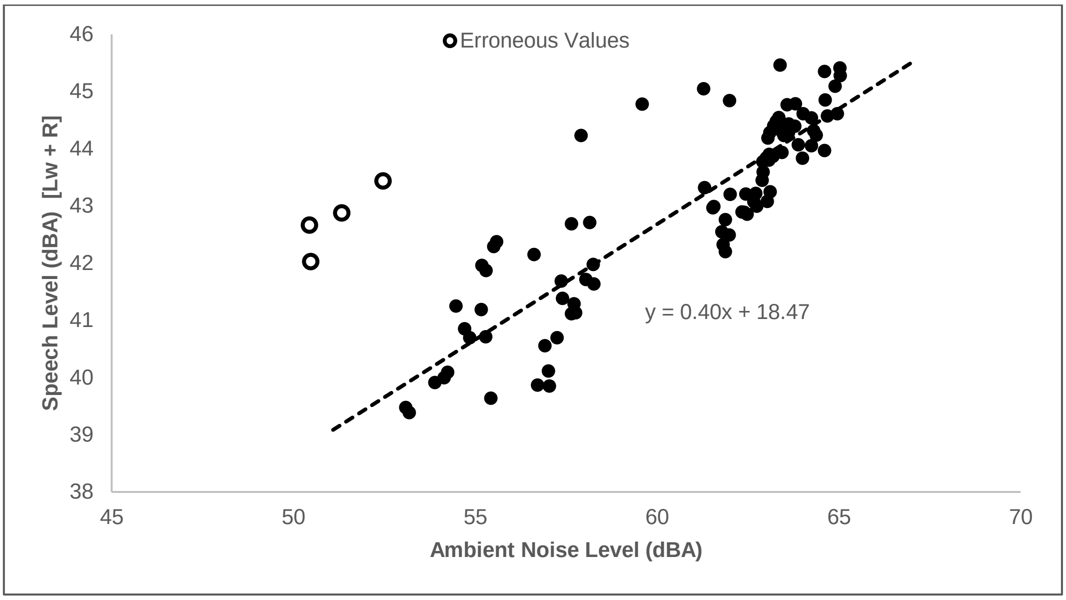


**Figure 5 - Derived contact centre Lombard coefficient**

The magnitude of the plot is not of interest, but the gradient of the slope shows the apparent Lombard effect observed at the contact centre. In this case there appeared to be a 0.4dB increase in voice levels for every 1dB increase in ambient noise.

### 4.1 Prediction of Ambient Noise Levels

As the occupancy of the open plan contact centre is known throughout the survey period, predictions of ambient noise levels can be made using a standard reverberant level model both with and without the Lombard effect.

The average speech sound power level of an occupant is defined by:

$$Lw = L_{S,A,1m} + 10\log_{10}(t) + 8.9 \qquad (4)$$

Where $t$ is the average percentage of time an occupant spends talking and 8.9dBA is the difference between the speech sound power level and the directional speech sound pressure level at 1m as set out in BS 3382:2012.

Substituting equation (4) into equation (2) gives a formula for calculating the ambient noise level based upon the occupancy levels of the open plan office. A “room effect” of -23dB is used, which is derived from the reverberation time measurements described in Section 3.1.

$$L_{NA} = L_{S,A,1m} + 10\log_{10}(t) + 8.9 + 10\log_{10}(N) + R \qquad (5)$$

In order to estimate the ambient noise level whilst accounting for the Lombard effect, equation (1) can be substituted into equation (5).

$$L_{NA} = 55 + c(L_{NA} - 45) + 10\log_{10}(t) + 8.9 + 10\log_{10}(N) + R \qquad (6)$$

This can then be rearranged to move all $L_{NA}$ terms to the left-hand side of the equation:

$$L_{NA} = \frac{1}{1-c}[55 - 45c + 10\log_{10}(t) + 8.9 + 10\log_{10}(N) + R] \qquad (7)$$

The parameter $t$ has been selected separately for each model in order to give the best agreement (least root mean squared error). The value of $t$ arrived at for each model was:

- Non-Lombard Model: $t = 54\%$
- Lombard Model: $t = 36\%$

A value of 50% represents contact centre workers being in a two-way telephone conversation for around 100% of the time. Therefore, it is proposed that the value of 36% is likely to be more realistic.

For the Lombard model, a Lombard coefficient of 0.40 was used, as derived in Section 4.

The results are shown in Figure 6 and Figure 7. For the model without Lombard effect it can be seen that there is a consistent underestimate of noise levels at high occupancy and an over-estimate of noise levels at low occupancy.

The Lombard effect model maintains a better agreement with the measured data at all occupancy levels.

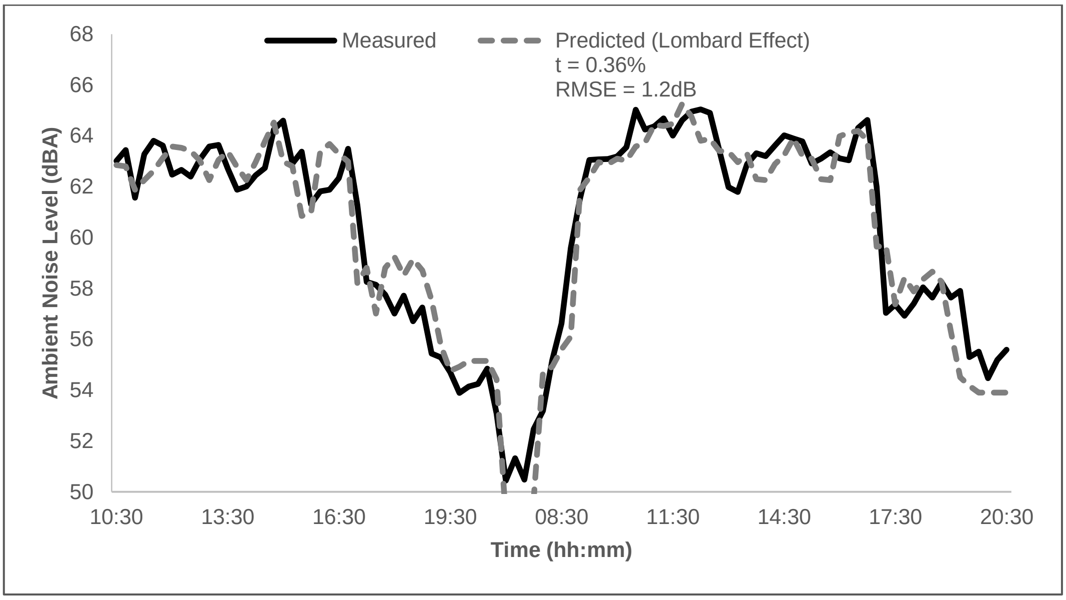


**Figure 6 - Ambient noise level predictions with the Lombard effect**

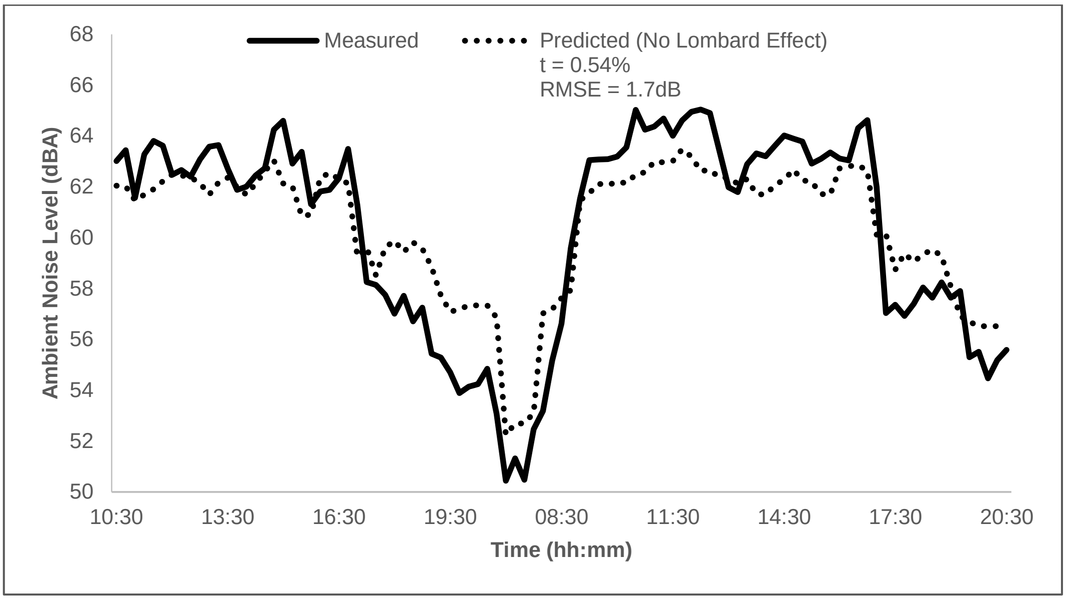


**Figure 7 - Ambient noise level prediction without Lombard effect**

### 4.2 Effect on Distraction and Privacy Distances

Other key room acoustic parameters of open plan offices are the distraction distance, $r_D$ and the privacy distance, $r_P$. These parameters are directly related to the speech transmission index (STI) and are defined as being the distance from a speaker where STI falls below 0.50 and 0.20 for distraction and privacy respectively.

The speech transmission index is proportional to the effective signal-to-noise ratio[9]. In a simplified model, the signal can be said to be equal to the speech level, $L_{S,A,1m}$ and the noise equal to the ambient noise level, $L_{NA}$.

The ambient noise level is directly proportional to the speech level, as shown in equation (5). Therefore, the Lombard effect results in both the signal and noise increasing by the same amount and as such, the signal to noise ratio is not affected.

This suggests that accounting for the Lombard effect in simulations, whilst having an impact on overall sound levels, should not have a significant impact on the calculation of distraction or privacy distances.

### 4.3 Application to Non-Sabine Spaces

Large open-plan offices are typically non-simple, non-diffuse spaces where simple Sabine calculations of reverberant noise-levels are unlikely to be accurate. Therefore, room acoustic modelling software should be used to predict the likely activity noise levels in such spaces.

The usual method for predicting the noise level within a space using room acoustic modelling software is to specify a number of sources with associated sound power levels and the sound pressure level at a location in the room given as an output.

This approach does not take into account the Lombard effect and a dynamic sound source, which changes level in response to the ambient noise level, would be required. At the time of writing the authors are not aware of simulation software which utilises dynamic sound sources and as such an alternative method is required.

The proposed method is to use geometrical acoustic modelling to predict the transfer function of the room. The exact methodology of how to achieve this is beyond the scope of this paper; however a simplified description of this approach is set out in the following steps:

- Create a grid of sound sources which approximates the open plan office workspace area.
- Model the resulting sound pressure level at representative locations, taking the average.
- The room transfer function can be found by subtracting the total sound power input into the model from the resulting sound pressure level output.

The predicted room transfer function is an estimation of the $R$ value used in previous sections. This can then be used in equation (7) to predict the ambient noise level, taking into account the Lombard effect.

A similar approach is used and discussed in further detail in a paper by Rindel and Christensen[10].

# 5 EFFECT OF OCCUPANCY DENSITY ON NOISE LEVELS

Equation (7) can be used to predict the activity noise level in open plan offices. If it is assumed that c is equal to 0.40 as previously derived, then this equation can be further simplified to:

$$L_{NA} = 76.5 + 16.7\log_{10}(Nt) + 1.7R \tag{9}$$

To explore the effect of occupancy density, the room effect term can be considered in terms of the Sabine model. In this case, $R = 10\log_{10}\left(4/_{A}\right)$, where $A$ is the area of Sabine absorption within a room. The acoustic absorption in call centres is typically provided by a Class A acoustic ceiling along with a carpeted floor. Therefore, assuming that the ceiling is ~100% absorbent and the floor is ~20% absorbent, the amount of acoustic absorption can be approximated by $A \cong 1.2S_{FLOOR}$ where $S_{FLOOR}$ is the office floor area. Substituting this into equation (9) gives:

$$L_{NA} = 85.2 + 16.7\log_{10}\left(\frac{Nt}{S_{FLOOR}}\right) \tag{10}$$

This can be re-arranged to give a solution for the occupancy density $\left(S_{FLOOR}/_{N}\right)$ required to achieve a certain ambient noise level.

$$\frac{S_{FLOOR}}{N} = t \times 10^{\left[\frac{(85.2-L_{NA})}{16.7}\right]} \tag{11}$$

The French standard for open-plan offices NF S31-199:2016[11], has specific guidance for call-centres, which suggests a maximum ambient noise level of 52dBA. Other literature recommends background noise levels below 55dBA to ensure acoustic comfort[8][12]. If a maximum ambient noise level of 55dBA is targeted then equation (11) can be simplified to show that the minimum area per occupant should be approximately $64.3t$. This is shown graphically in Figure 8.

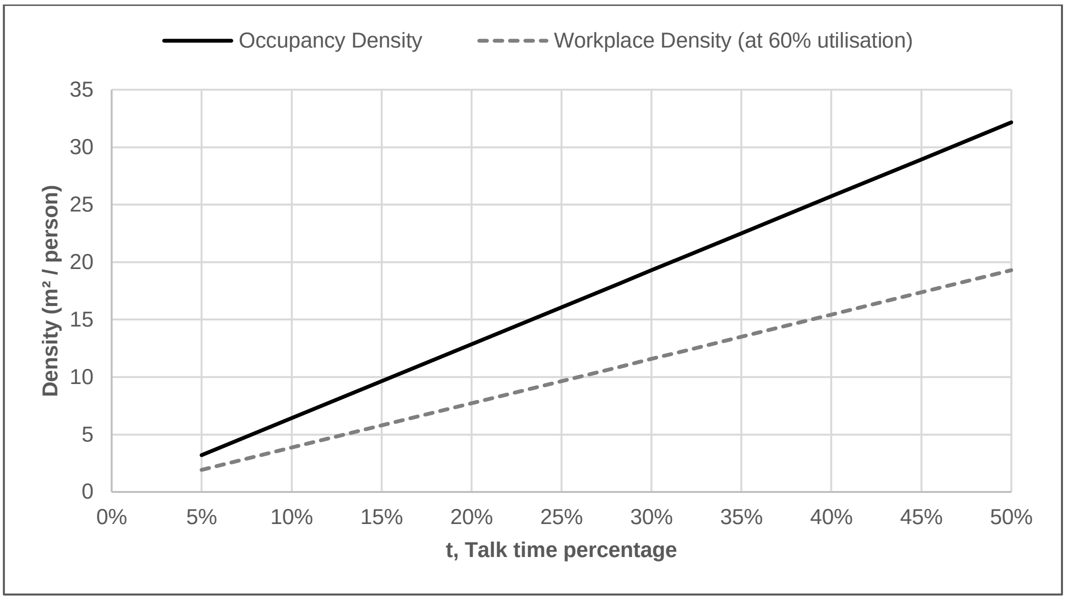


**Figure 8 – Occupancy Density vs % talk time to achieve 55dBA ambient noise level**

A survey by the British Council for Offices in 2013[13] shows that the mean occupancy density is 10.9m²/workplace, the distribution is shown in Figure 9. By comparison to Figure 8 it can be seen that this average level of occupancy density would only result in ambient noise levels below 55dBA at a relatively low level talk time of 17%, which is unlikely to be realistic in contact centre scenarios.

The distinction between workplace density and occupancy density should be noted. Buildings are rarely, if ever, occupied to maximum capacity. According to [13] studies regularly show that the number of workplaces being used at any one time is consistently between 50% and 60%. The workplace density, assuming a 60% utilisation, in order to achieve a 55dBA ambient noise level is also shown in Figure 8.

Accounting for the under-utilisation of workplaces means that reasonable noise levels are much more likely to be achieved. This highlights the risk that as organisations work towards higher utilisation of workplaces with flexible working, ambient noise levels could increase significantly.

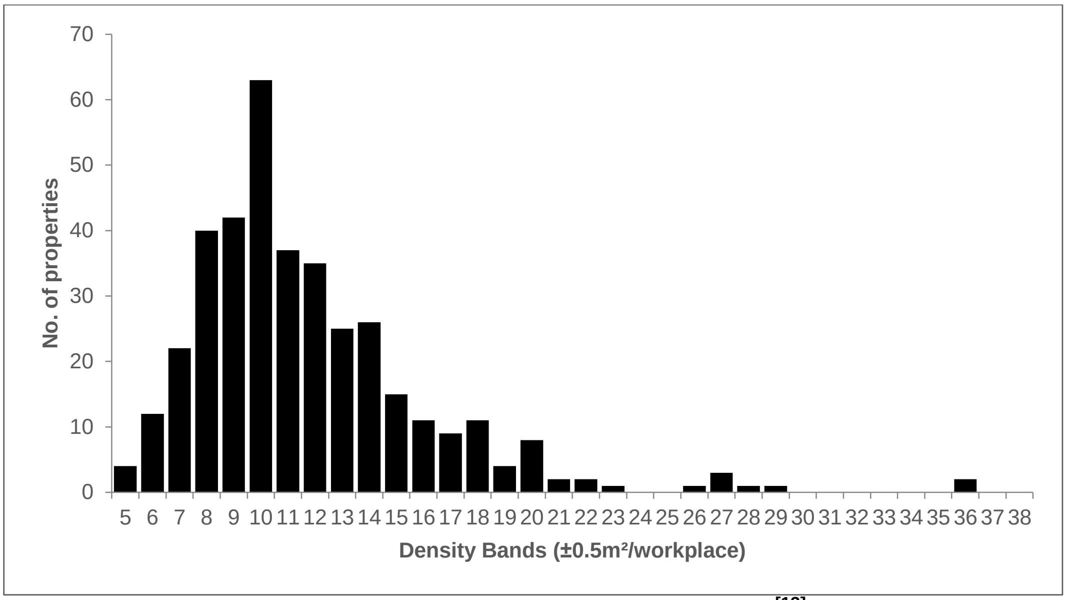


**Figure 9 - BCO Occupier Density Survey[13]**

# 6 CONCLUSION

This paper has explored the Lombard effect specifically with regards to its relevance in open plan contact centres. We have found that the Lombard Effect does appear to operate significantly in open plan call centres and that, based on in-situ measurements of a large call centre, a Lombard coefficient of 0.4 appears to be applicable.

Useful relationships have been derived relating ambient noise levels in open plan offices to the occupancy density.

# 7 REFERENCES


1. BS EN ISO 3382-3:2012, Acoustics – Measurement of room acoustic parameters.
2. ISO 9921. Ergonomics – Assessment of speech communication.
3. H. Lazarus, Prediction of Verbal Communication in Noise – A Review: Part 1, Applied Acoustics, Volume 19, Issue 6, 439-464. (1986).
4. ANSI S3.5-1997 (R 2007), Methods for the calculation of the speech intelligibility index.
5. A. C. C. Warnock & W. T. Chu, Voice and background noise levels measured in open offices. (2002).
6. J. B. Moreland, Ambient noise measurements in open-plan offices, The Journal of the Acoustical Society of America, Volume 83, Issue 4. (1988).
7. E. Nilsson & B. Hallström, Acoustic design of open-plan offices. (2010).
8. N. Trompette & J. Hatillon, Survey of noise exposure and background noise in call centers using headphones, Journal of Occupational and Environmental Hygiene, Volume 9, Issue 6, 381-386. (2012)
9. BS EN ISO 60268-15:2011, Objective rating of speech intelligibility by speech transmission index.
10. J. Rindel & C. Christensen, Dynamic sound source for simulating the Lombard effect in room acoustic modelling software. (2012)
11. NF S31-199: 2016. Acoustics - Acoustics performances of open-plan offices
12. ISO 11690-1:1996. Acoustics —Recommended Practice for the Design of Low-Noise Workplaces Containing Machinery—Part 1: Noise Control Strategies
13. British Council for Office, Occupier Density Study. (2013)